ERC Program Overview

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INTRODUCTION

The carbonate fuel cell promises highly efficient, cost-effective, environmentally superior power generation from pipeline natural gas, coal gas, biogas, and other gaseous and liquid fuels. ERC has been engaged in the development of this unique technology since the late 1970s, primarily focusing on the development of the Direct Fuel Cell (DFC) technology [1-6] pioneered by ERC. The DFC design incorporates the unique internal reforming feature which allows utilization of a hydrocarbon fuel directly in the fuel cell without requiring any external reforming reactor and associated heat exchange equipment. This approach provides upgrading of waste heat to chemical energy; thereby, it contributing to higher overall efficiency for conversion of fuel energy to electricity with low levels of environmental emissions. Among the internal reforming options, ERC has selected the Indirect Internal Reforming (IIR) - Direct Internal Reforming (DIR) combination as its baseline design.

ERC plans to offer commercial DFC power plants in various sizes, initially focusing on the MW-scale units. The plan is to offer standardized, packaged MW-scale DFC power plants operating on natural gas or other hydrocarbon-containing fuels for commercial sale by the end of the decade. These power plants, which can be shop-fabricated and sited near the user, are ideally suited for distributed generation, industrial cogeneration, and uninterrupted power for military bases. After gaining experience from the early MW-scale power plants, and with maturing of the technology, ERC expects to introduce larger power plants operating on natural gas and/or coal gas or other fuels in the beginning of the 21st century.

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ERC has completed a technology program for product design verification, a predecessor of the current program, where the power plant design as well as the technology development were carried out to support a full-size field demonstration. These activities culminated in 130 kW stack tests in ERC's subscale power plant, subscale stack tests in utility and industrial sites around the world, and a 1.8 MW power plant design for demonstration at a utility site. The design and procurement were completed and testing of this world's largest multi-megawatt advanced fuel cell demonstration plant has begun. The demonstration accomplishments are addressed in a separate paper at this conference. Built on these advances, ERC launched the present phase of the product development sponsored by government and private-sector cost-share, leading to technology and system optimization for cost reduction, commercial design development, and system demonstration.

OBJECTIVES AND APPROACH

This program is designed to advance the carbonate fuel cell technology from the current power plant demonstration to the commercial design in an approximately five-year period. The specific objectives selected to attain the overall program goal are:

- Define power plant requirements and specifications,
- Establish the design for a multifuel, low-cost, modular, market-responsive power plant,
- Resolve power plant manufacturing issues and define the design for the commercial-scale manufacturing facility,
- Define the stack and balance-of-plant (BOP) equipment packaging arrangement and module designs,
- Acquire capability to support developmental testing of stacks and critical BOP equipment to prepare for commercial design, and
- Resolve stack and BOP equipment technology issues, and design, build, and field test a modular prototype power plant to demonstrate readiness for commercial entry.

A seven-task program, dedicated to attaining objective(s) in the areas noted above, was initiated in December 1994. Accomplishments of the past program year are discussed in this paper.

PROJECT DESCRIPTION

ERC is currently in the second year of the five year program, for development and demonstration of a MW-class power plant supported by DOE/METC with additional funding from DOD/DARPA and the ERC Team. Figure 1 shows key program elements (shaded area) and their interrelationships. The product definition and specification have been derived with input from potential users, including the Fuel Cell Commercialization Group (FCCG). Detailed power plant system and packaging designs are being developed using stack and BOP development results. A

MW-scale prototype modular power plant representative of an early production unit (EPU) is planned to be constructed and tested. Based on the experience and data generated in the current program, ERC also plans to acquire manufacturing capability for EPUs through expansion of the existing Torrington production facility.

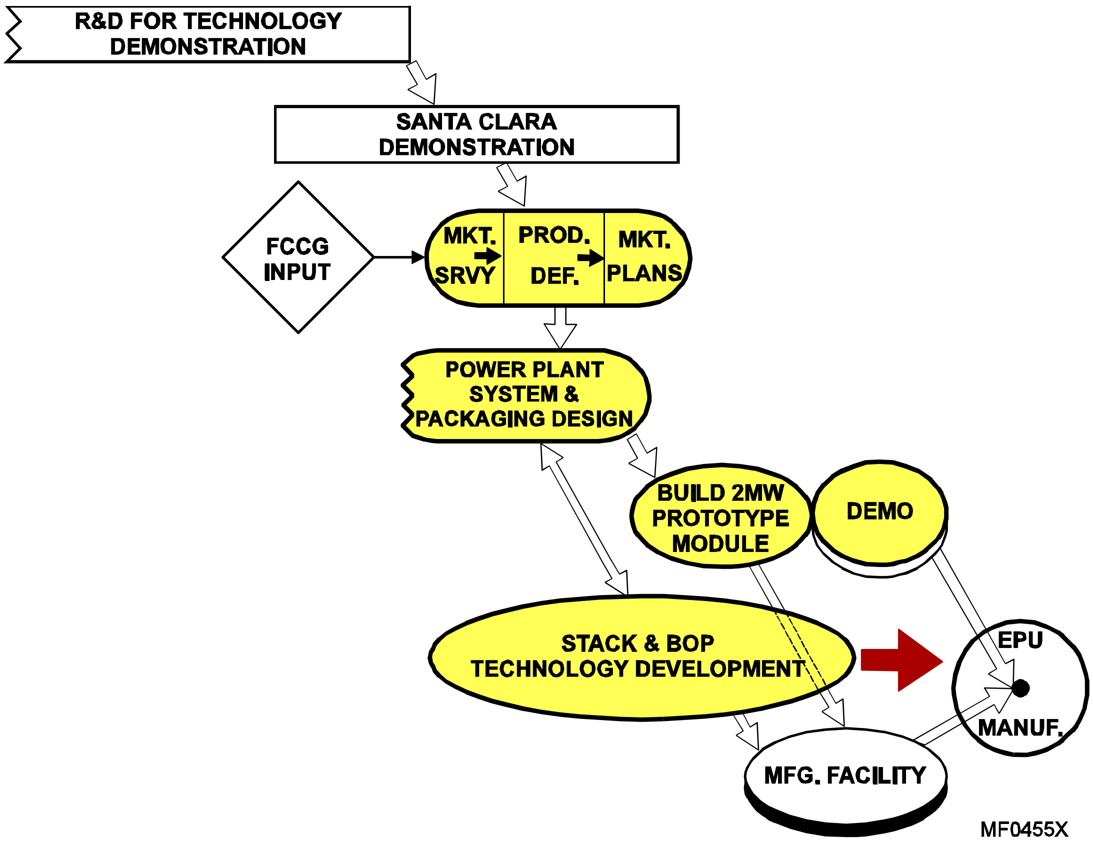


Figure 1. EFFORT AND INTERACTION OF KEY PROJECT ELEMENTS:
The Program will Result in the Early Production Commercial Product Design

The project team has been assembled to supplement all relevant expertise required for product design, improvement, verifications, and marketing. The team consists of:

Energy Research Corporation (ERC), R&D arm focusing on market-entry product improvement, coordinating the effort under all program areas;

Fuel Cell Engineering (FCE), a subsidiary of ERC, concentrating on product definition oversight and overall plant construction management and customer service;

Fuel Cell Manufacturing Corporation (FCMC), another subsidiary of ERC, focusing on manufacturing process development and stack module fabrication;

Fluor Daniel Inc. (FDI), Irvine, CA, assisting FCE in power plant and manufacturing plant designs;

Jacobs Applied Technology (JAT), Orangeburg, SC, assisting in assembly and packaging of fuel cell stacks and BOP modules;

Fuel Cell Commercialization Group (FCCG), Washington, D.C., a group of potential buyers of early production units, collaborating with FCE in product definition, system design, utility system planning and information distribution;

Motoren-und Turbinen-Union (MTU), Germany, an affiliate of Daimler Benz, conducting parallel stack technology development focusing on endurance, cost reduction, and cogeneration applications.

RESULTS/ACCOMPLISHMENTS

ERC is developing the detailed design of the commercial entry MW-class power plant. In collaboration with the FCCG, the product requirements and specifications have been derived. The planned baseline power plant is rated at 2.85 MW on natural gas and has a heat rate of 6.22×10^6 J/kWh (5900 Btu/kWh; 58% LHV). Additional optional features will be available to include non-standard site conditions and other fuels. The FCCG members are potential buyers of the EPUs. A model EPU purchase contract has been developed with the FCCG Board of Directors and first Letter of Intent for an EPU purchase has been obtained.

In parallel, the baseline product design has progressed to the final design phase in collaboration with FDI. The preliminary product design, which also included parametric optimization, major component vendor interaction, and cost estimation, has been completed during the past year. The power plant approach consists of several factory-constructed truck-transportable modules. A computer-generated power plant layout is shown in Figure 2. The proposed power plant is expected to have a gross output of 3.03 MW, providing net 2.85 MW AC. The parasitic power loss is approximately 6%, of which, inverter, step-up transformer, BOP motors, and miscellaneous loads consume 2%, 1%, 2%, and 1%, respectively.

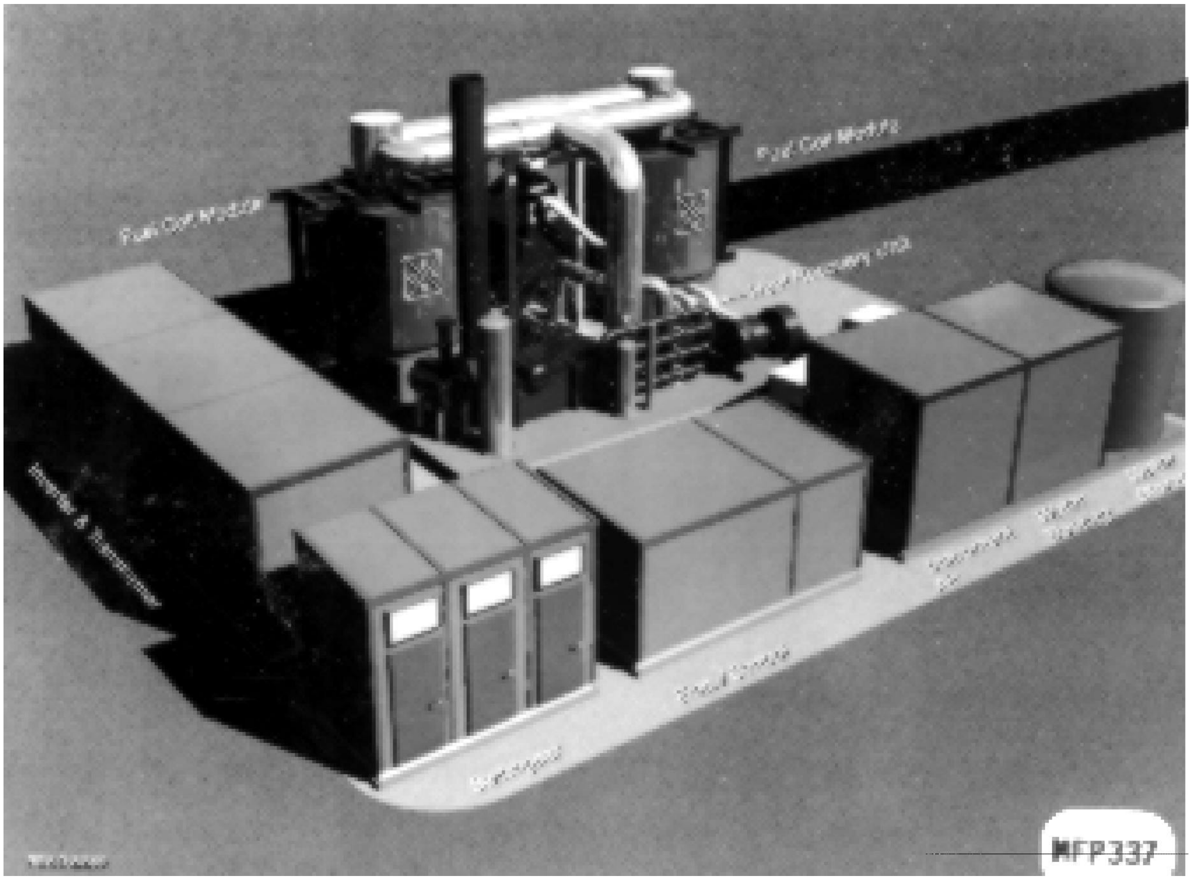
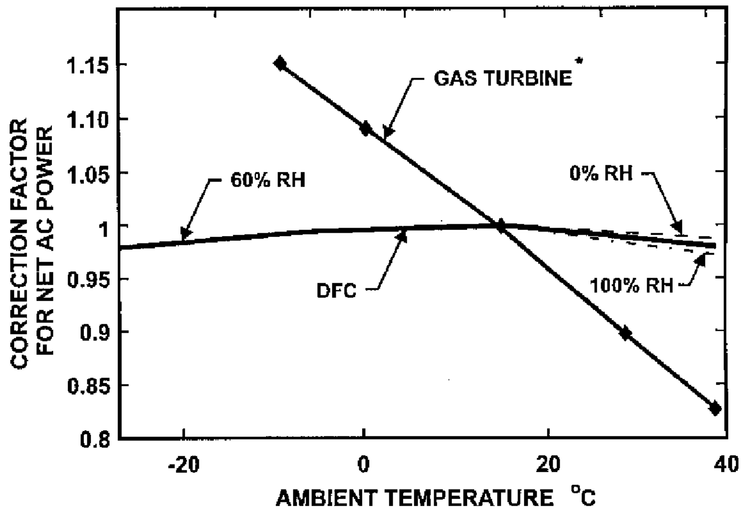


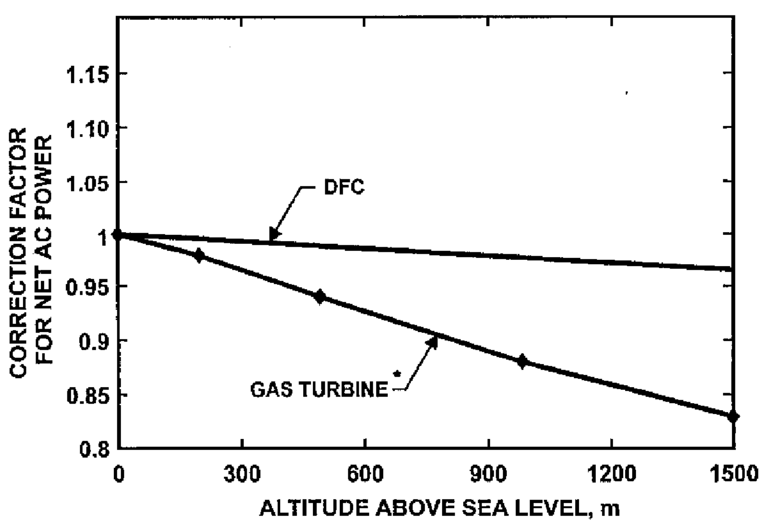
Figure 2. BASELINE COMMERCIAL POWER PLANT LAYOUT:
The 2.85 MW Power Plant Design has Progressed to the Final Design Phase

Standard conditions for ERC's power plant design include a 15°C ambient temperature, 60% relative humidity, and sea level elevation. The effects of ambient temperature from -20°C to 43°C, relative humidity from 0 to 100% and elevation up to 1500 m on the power plant rating have been investigated (Figures 3 and 4). The net maximum impact on plant rating was found to be ~3%. This is extremely low when compared with the state-of-the-art turbine-based power plants which may suffer over 10% capacity loss with change of ambient conditions. The DFC power plant rating is also essentially unaffected for fuel heating value change from 33.5×10^6 J/m^3 to 37.2×10^6 J/m^3 (900 Btu/scf to 1,000 Btu/scf). This heating value range covers most of the U.S. pipeline natural gas. Also, a preliminary Reliability and Maintainability (RAM) assessment of the power plant was made using the UNIRAM software and assessment methodology consistent with the analysis described in the published EPRI Report TR-101107. The RAM study concluded that the base case commercial fuel cell power plant is expected to achieve an availability in excess of 95%, with a one week per year scheduled outage period. Additionally, the criticality analysis demonstrated that the BOP equipment is reliable and available.



*Source: Gas Turbine Performance - New Application and Test Correction Curves, Presented at the International Gas Turbine and Aeroengine Congress and Exposition, Houston, Texas, June 5-8, 1995

Figure 3. DFC POWER PLANT CORRECTION FACTORS FOR AMBIENT TEMPERATURE AND RELATIVE HUMIDITY:
DFC Output is not Sensitive to Ambient Temperature and Humidity Changes



* Source: Gas Turbine Performance-New Application and Test Correction Curves, Presented at the International Gas Turbine and Aeroengine Congress and Exposition, Houston, Texas, June 5-8, 1995

Figure 4. DFC POWER PLANT CORRECTION FACTORS FOR ALTITUDES:
Altitude Effect on DFC is Small

In the preliminary design development phase, the 2.85 MW DFC plant dynamic simulation model was developed to evaluate transient behavior, equipment design parameters, and control strategies. The model used Aspen Tech's Speedup program to integrate the fuel cell and BOP equipment models for simulating appropriate start-up, steady state, shutdown, and load transient conditions, as well as system upsets to gain operating insights. As an example, the dynamic simulation results shown in Figure 5 indicate that the output power can be ramped from 25% to 100% of the rated load in less than 10 minutes, a feature desired by some power plant buyers. The results of the dynamic simulations will be incorporated into the plant design as it evolves to the final stage.

An equipment list was prepared and major equipment vendors were contacted with equipment specifications for design and budgetary cost estimates. A cost estimate based on budgetary quotes from vendors indicated that the capital cost of $1,250/kW (1995 dollars) is achievable for the matured commercial product. This was further confirmed by an independent stochastic review of design assumptions and cost models. Variances of design assumptions and cost elements were defined and a Monte Carlo simulation was conducted to identify power plant cost profile. It was observed that the probability of attaining the cost goal of <$1250/kW is better than 75% (Figure 6).

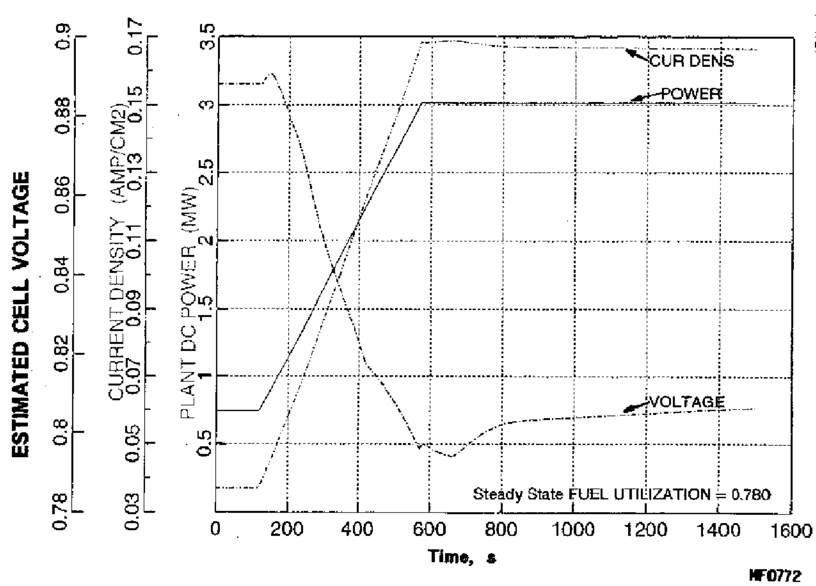


Figure 5. POWER RAMP FROM QUARTER TO FULL LOAD:
Rated Power can be Achieved from a 1/4 Rated Load in 10 Minutes

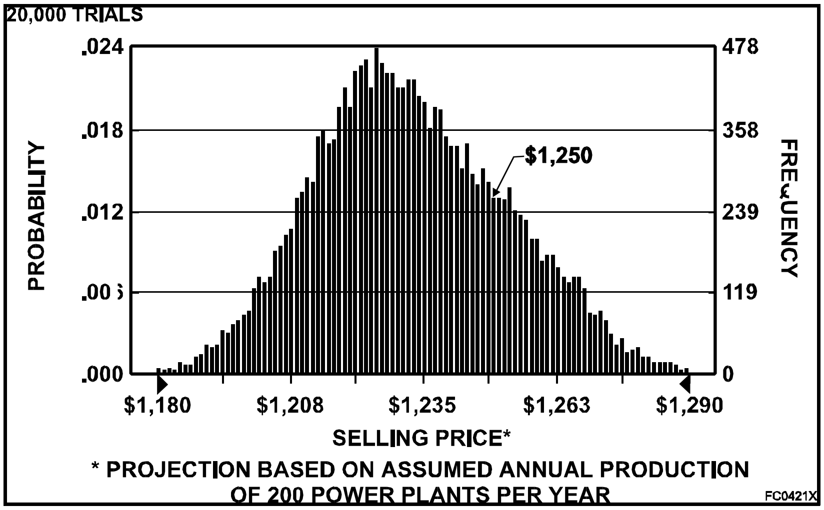


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Figure 6. TOTAL POWER PLANT MANUFACTURING COST FORECAST ($/kW):
Probability of Meeting the Product Cost Goal of $1250/kW (1995 $) is Better than 75%

The power plant operating and maintenance costs have been analyzed (Table 1). Because the power plant is expected to operate automatically, the fixed and variable operating cost is projected to be low, ~4 mills/kWh. Fuel cell replacement cost is projected to be 7 mills/kWh, and the capital carrying charge is estimated to be 16 mills/kWh. Assuming fuel cost to be $2.32/(10^9J) ($2.45/MM Btu), the 30-year levelized cost-of-electricity (COE) is projected to be about 4 cents.

Table 1. 30-YEAR LEVELIZED O&M COSTS:.
DFC Cost-of-Electricity is Projected to be ~4 Cents

Element	mills/kWhr (Constant 1995$)
Installed Cost	16
Fixed	1
Variable	4
Fuel @ $2.45/MMBtu	14
Stack Replacement	7
COE	42

As discussed earlier, the ERC standard product can provide several optional features such as grid-independent operation. Another optional configuration is dual fuel operation, using natural gas or the DOD logistic fuels (JP-8 and diesel), for fixed base power plant applications. The logistic fuel operation requires a front-end fuel processor to convert logistic fuels to fuel cell compatible feed stream. The diesel and jet fuel processing design information is being developed at ERC in parallel. Originally, under a Navy SBIR program, ERC tested a labscale carbonate fuel cell stack on a model diesel-like fuel (Exxsol) in 1991-93 using an adiabatic prereformer to convert liquid fuel to methane. More recently under the DARPA/NASA sponsored program, ERC verified a 32 kW size stack operation on jet fuel (JP-8) and diesel (DF-2) in system integrated tests, employing ERC's diesel-to-methane fuel processing approach. The stack was also tested at landfill gas simulated system condition. The stack performance comparison on different fuel systems is shown in Figure 7. The cathode gas composition for each fuel test was simulated to represent the system conditions. Stack operability on multiple fuels was verified. The stack performance at different conditions indicates that only a slight output power derating (~5%) of the baseline 2.85 MW product is expected for DOD fuels and landfill gas operations. A 3 MW logistic fuel preprocessor design will be defined based on the 32 kW size breadboard fuel preprocessor experience. The diesel fuel processor as available from this parallel effort could be interfaced with the baseline natural gas power plant design so that the DFC plant can be used for the dual fuel (diesel and pipeline natural gas) DOD application.

To reduce cell costs and achieve optimum packaging of stacks in the truck-transportable module, the cell area was scaled-up from 6000 cm^2 (2 ft x 3 ft) to 9000 cm^2 (2 ft x 4 ft) nominal size. The capital equipment required for the manufacture of the large area repeating cell components was commissioned. The equipment list includes a pneumatic trim sizing press, a precision sizing machine, and a large area hydraulic press (shown in Figure 8). In parallel with scaleup, efforts were focused to establish process and/or equipment specifications to improve component tolerance and/or reproducibility. As an example, the new press was specified to produce parts better than dimensional tolerance specifications.

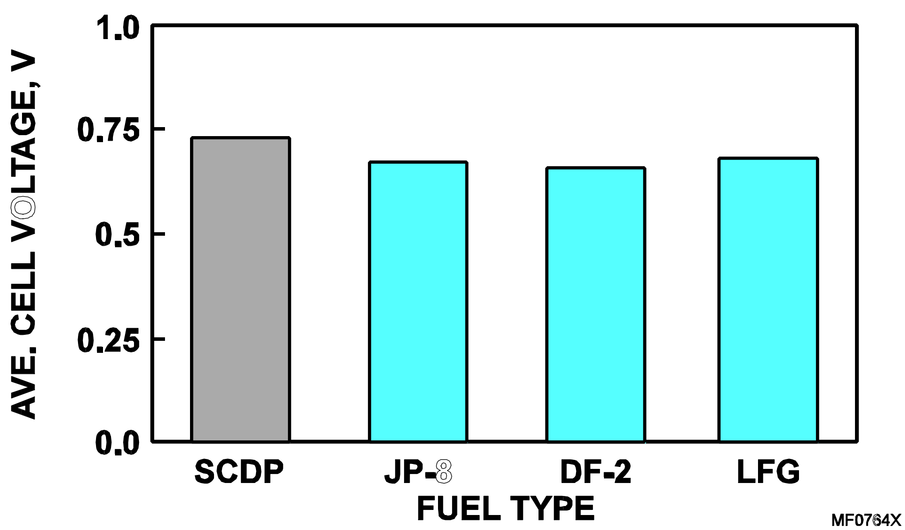

Figure 7. 30 kW STACK PERFORMANCE COMPARISON ON DIFFERENT FUELS (131 mA/cm^2, 70% Fuel Util., 656°C):
Less than 5% Derating of Product is Expected for the Military Fuels

Figure 8. LARGE AREA HYDRAULIC PRESS:
Successfully Commissioned and Used for Managing Tolerance of 9000 cm^2 Cell Packages

An advanced bipolar plate design, eliminating an expensive vendor processing operation, has been developed. A low-cost wet seal corrosion protection process developed by MTU in the parallel technology effort was successfully scaled-up and implemented in the full-area bipolar plate. The 11,000 hour corrosion result of this new low-cost process, compared with the baseline design in Figure 9, indicates no stability issue. These bipolar plate design modifications have resulted in approximately 40% cost reduction. Large area (9000 cm^2) anode, cathode and matrix components were manufactured using the newly commissioned equipment. A photograph of the 9000 cm^2 cell package produced is shown in Figure 10. An automated final cell package quality control measurement system has been developed. The initial 9000 cm^2 cell area packages showed 35% improvement in thickness tolerance over the previous (6000 cm^2 cell) experience.

Efforts were also focused on process optimization for increased productivity as well as overall quality improvement. Anode tape casting is fully developed and belt speed optimization as well as automatic blade height adjustment designs were implemented to improve production rates as well as dimensional tolerance. Matrix tape cast process optimization is also in progress. These efforts were successful in reducing tape slurry preparation time by a factor of thirty, and casting time by a factor of three. In addition to production rate improvement, a 30% reduction in matrix green tape thickness tolerance was achieved through tape caster improvements.

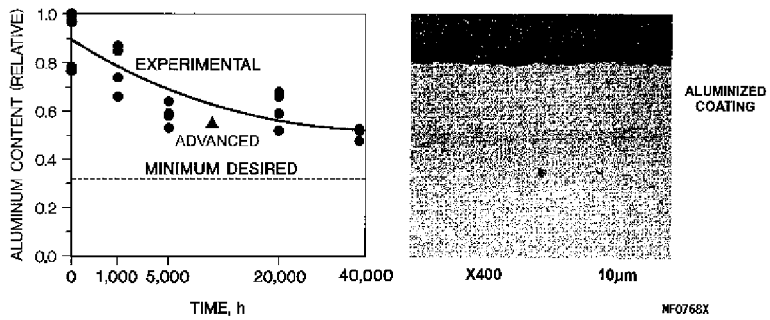

Figure 9. WET SEAL CORROSION CHARACTERIZATION:
The Baseline Design (•) Expected to Last for 40,000 hours;
the Advanced Low-Cost Design (▲) also Appears to be Stable

Figure 10. FULL-AREA CELL PACKAGE:
The 9000 cm^2 Cell Components Fabricated at FCMC to Verify Scaleup

The indirect internal reformer unit weight has been reduced by 60% over the 1995 design. The first stack test using this lightweight reformer design and the scaled 9000 cm^2 cell components (a photograph of the stack is shown in Figure 11) has been completed. The 10-cell IIR-DIR stack was tested in conjunction with an internally insulated enclosure. Performance of this large cell area stack is compared with previous 6000 cm^2 area lightweight and Santa Clara type heavy designs in Figure 12. The results indicate that the scaleup of the lightweight component has been achieved without any performance penalty. Cell temperature profile corresponding to 160 mA/cm^2 operation is shown in Figure 13. The results show that the large area DFC stack has achieved an excellent temperature uniformity.

Prior to building the full-height stack, a full-size stack simulator has been fabricated for verification of assembly procedures, designs of the manifolds, and gas flow distribution design. A photograph of the simulator is shown in Figure 14. A gas flow model and the simulator experiments were utilized to define tall stack manifold designs to achieve cell-to-cell uniform flow distribution. Less than 2% flow variation between cells for fuel as well as oxidant is projected. A fuel cell module will contain four full-size stacks. The gas flow distribution system designs within the module were defined and the performances were verified in cold tests. The expected fuel flow variations between the stacks in a module are shown in Figure 15; fuel flow variations are expected to be less than 1%. ERC is now completing construction of a 400 kW subscale power plant which will be used to verify the performance of the full height stack and BOP equipment in system tests. This subscale power plant is representative of the standard power plant design.

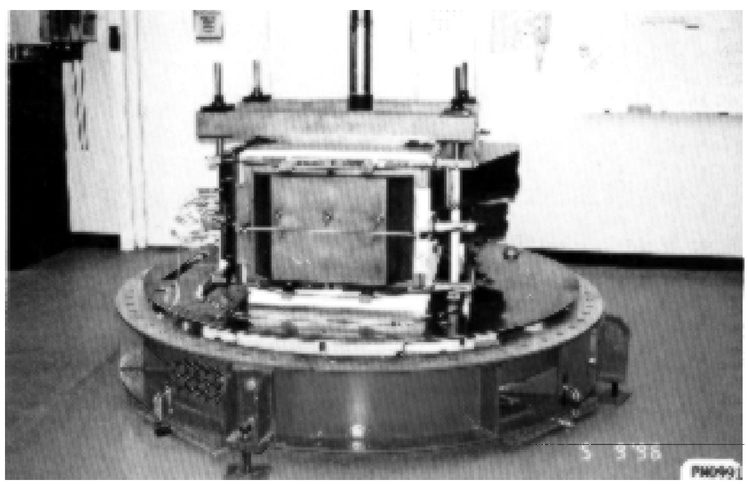

Figure 11. 10-CELL 9000 cm^2 CELL AREA STACK:
Stack Module Compatible Lightweight Stack Hardware Design Verifier

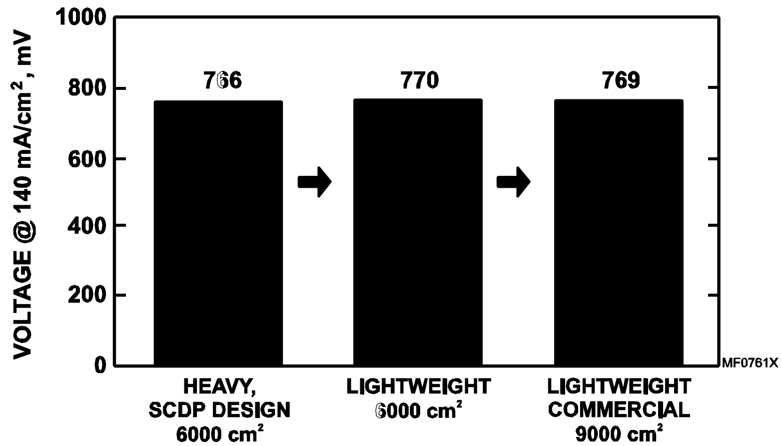

Figure 12. LIGHTWEIGHT LARGE CELL AREA STACK PERFORMANCE:
Cell Area Scale-up Achieved Without Performance Penalty

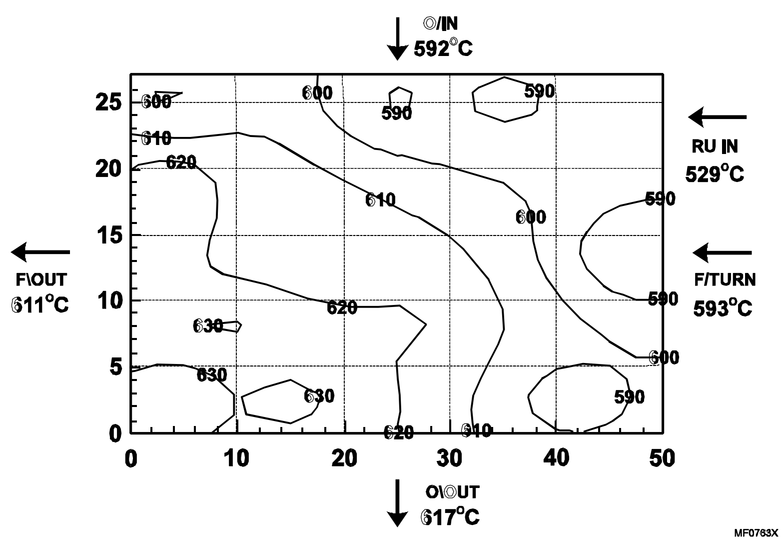

Figure 13. TEMPERATURE PROFILE AT 160mA/cm^2 (9000 cm^2, 10-CELL DFC STACK):
Excellent Temperature Uniformity Achieved

Figure 14. FULL-HEIGHT 9000 cm^2 CELL AREA STACK SIMULATOR:
Verified Stack Assembly Procedures and External Hardware Designs

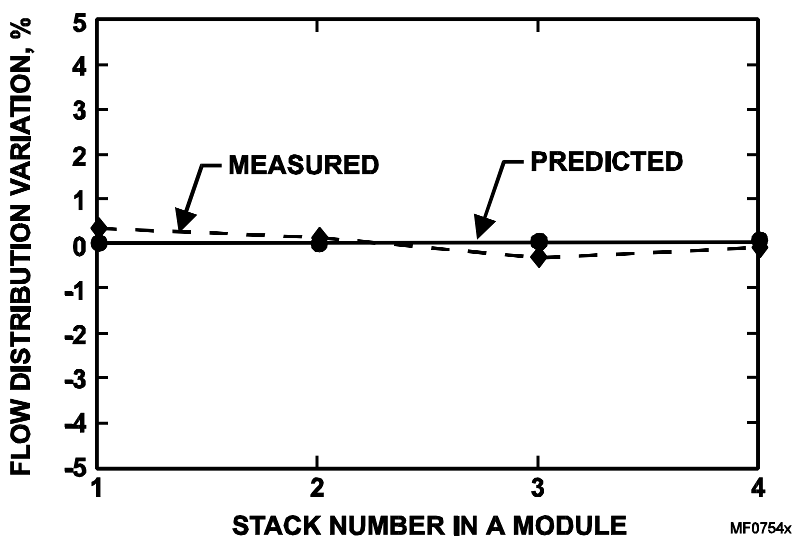

Figure 15. FUEL FLOW DISTRIBUTION BETWEEN STACKS IN A MODULE:
~0.5% Flow Variations Expected

ERC is in the final design phase of the commercial power plant. Equipment packaging approaches and plant layout are being finalized. The cell area scaleup is completed. Components cost reduction, performance enhancement, and life extension efforts are on track. Future activities will focus on finalization of power plant design, and verification of stack module enclosure and full-height stack designs.

ACKNOWLEDGEMENT

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